

1. Introduction

An investigation of soot formation within freely-propagating laminar premixed flames is described. The findings of the research are relevant to several problems of society, as follows: the particulate soot pollutant emissions from flames, the radiant heat loads from combustion processes, the hazards of terrestrial and spacecraft fires, and the practical development of methods of computational combustion. The research was carried out in two phases, as follows: (1) study of soot formation in freely-propagating laminar premixed flames, and (2) study of the optical properties of soot needed to develop nonintrusive optical ways of finding soot structure within freely-propagating laminar premixed flames.

It is widely recognized that soot processes in flames are a major unresolved problem of combustion science. This observation has motivated numerous studies of the physical, optical and reactive properties of soot during combustion processes. This research has also disclosed some problems concerning studies of soot formation in burner-stabilized laminar premixed flames that frequently have been used for measurements of soot phenomena, as follows: (1) flame structure is sensitive to minor burner construction details so that laboratory-to-laboratory reproducibility is not very good, (2) consistent burner behavior over the lengthy test programs needed to define soot formation properties are hard to achieve due to poorly understood effects of burner aging, (3) it is difficult to accurately define near burner flame properties due to the intrusion of the flame holder, (4) it is difficult to quantify conductive, convective and radiative heat losses to the burner that are needed to define flame temperature properties, (5) it is difficult to define flow velocities near the burner where the flow is multidimensional and velocities change rapidly with streamwise distance due to effects of buoyancy, and (6) it is difficult to carry out fundamental numerical simulations of premixed flame properties due to the multidimensional effects and the complex geometries of flame holders (e.g., porous plates). These problems can largely be avoided, however, by studying freely-propagating laminar premixed flames at conditions where the flames have stable and smooth spherical flame surfaces as they propagate. The feasibility of experiments along these lines to study processes of soot formation is considered in the first part of the present study.

A key measurement needed to find soot surface growth rates and surface areas for soot surface reactions in flames is soot structure. Recent studies in flames generally have used thermophoretic sampling and analysis by transmission electron microscopy (TEM) to find soot structure. This approach is not very effective for freely-propagating premixed flames, however, because the process of soot formation is never stationary at any point within such flames. A rational alternative approach is to measure soot structure optically using nonintrusive laser scattering and absorption techniques. Recent work in this area has disclosed that past nonintrusive optical measurements adopted questionable soot optical property theories and new

methods must be devised. Thus, developing new nonintrusive optical methods to find soot structure properties is considered in the second part of the present study.

The following description of the research is relatively brief. Additional details can be found in the archival publications, the papers, the conference proceedings and the theses resulting from the investigation that are summarized in Table 1. This table also provides a summary of invited and contributed oral presentations of the research results, honors and awards obtained during the grant period and the individuals who participated in the investigation. Finally, for convenience, several articles resulting from the research are reproduced in Appendices A-L.

The laminar premixed flame and soot optical property phases of the present investigation are considered in turn in the following. The discussion of each phase stands alone and has its own conclusions; therefore, each phase can be read independently if desired.

Table 1. Summary of Investigation*

Archival Publications (articles and book chapters):

Dai, Z. and Faeth, G.M. (2000) Hydrodynamic suppression of soot formation in laminar coflowing jet diffusion flames. *Proc. Combust. Inst.*, 28, 2085-2092.

El-Leathy, A.M., Xu, F., Kim, C.H. and Faeth, G.M. (2002) Soot surface growth in laminar hydrocarbon/air diffusion flames. *AIAA J.*, in press.

Faeth, G.M. (2001) Gaseous laminar and turbulent diffusion flames. *Microgravity Combustion Science* (H.D. Ross, ed.), Academic Press, New York, Chapt. 3, (pp. 83-182).

Krishnan, S.S., Lin, K.-C. and Faeth, G.M. (2001) Extinction and scattering properties of soot emitted from large buoyant turbulent diffusion flames. *J. Heat Transfer* 123, 331-339.

Urban, D.L., Yuan, Z.-G., Sunderland, P.B., Linteris, G.T., Voss, J.E., Lin, K.-C., Dai, Z., Sun, K. and Faeth, G.M. (1998) Structure and soot properties of nonbuoyant ethylene/air laminar jet diffusion flames. *AIAA J.* 36, 1346-1360.

Urban, D.L., Yuan, Z.-G., Sunderland, P.B., Lin, K.-C., Dai, Z. and Faeth, G.M. (2000) Smoke-point properties of nonbuoyant round laminar jet diffusion flames. *Proc. Combust. Inst.* 28, 1965-1972.

Xu, F., Sunderland, P.B. and Faeth, G.M. (1997) Soot formation in laminar premixed ethylene/air flames at atmospheric pressure. *Combust. Flame* 108, 471-493.

Xu, F., Lin, K.-C. and Faeth, G.M. (1998) Soot formation in laminar premixed methane/oxygen flames at atmospheric pressure. *Combust. Flame* 115, 195-209.

Xu, F. and Faeth, G.M. (2000) Structure of the soot growth region of laminar premixed methane/oxygen flames. *Combust. Flame* 121, 640-650

Xu, F. and Faeth, G.M. (2001) Soot formation in laminar acetylene/air diffusion flames at atmospheric pressure. *Combust. Flame* 125, 804-819.

Xu, F., El-Leathy, A.M., Kim, C.-H. and Faeth, G.M. (2002) Soot surface oxidation in laminar hydrocarbon/air diffusion flames at atmospheric pressure. *Combust. Flame*, in press.

Xu, F., Dai, Z. and Faeth, G.M. (2002) Flame shapes of nonbuoyant laminar jet diffusion flames. *AIAA J.*, in press.

Papers and Conference Proceedings:

Dai, Z., Xu, F. and Faeth, G.M. (2001) "Shapes of Soot-Free Hydrocarbon/Air Laminar Coflowing Jet Diffusion Flames," 39th Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 2001-1078.

Dai, Z. and Faeth, G.M. (2000) "Shapes of Nonbuoyant Laminar Jet Diffusion Flames at Soot- and Smoke-Point Conditions," Proceedings of the Spring Technical Meeting 2000, Canadian Section of the Combustion Institute, Ottawa, pp. 22-1 to 22-6.

Dai, Z. and Faeth, G.M. (2000) "Soot- and Smoke-Point Properties of Laminar Coflowing Jet Diffusion Flames," Proceedings of the Spring Technical Meeting, Central States Section, The Combustion Institute, Pittsburgh, PA, pp. 39-44.

El-Leathy, A.M., Xu, F. and Faeth, G.M. (2001) "Soot Growth in Hydrocarbon-Fueled Laminar Diffusion Flames at Atmospheric Pressure," 39th Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 2001-1077.

El-Leathy, A.M., Xu, F. and Faeth, G.M. (2001) "Structure and Early Soot Oxidation Properties of Laminar Diffusion Flames," Sixth International Microgravity Combustion Workshop, NASA/CP-2001-210826, pp. 169-172.

El-Leathy, A.M., Xu, F. and Faeth, G.M. (2001) "Soot Growth and Oxidation in Laminar Jet Diffusion Flames," Proceedings of the Spring Technical Meeting, The Canadian Section, The Combustion Institute, Pittsburgh, 2001, Pittsburgh.

El-Leathy, A.M., Xu, F. and Faeth, G.M. (2001) "Structure and Soot Formation Properties of Laminar Diffusion Flames," Sixth International Microgravity Combustion Workshop, NASA/CP-2001-210826, Washington, pp. 325-328.

El-Leathy, A.M., Xu, F. and Faeth, G.M. (2001) "Early Soot Oxidation in Hydrocarbon-Fueled Laminar Jet Diffusion Flames at Atmospheric Pressure," Proceedings of 2nd Joint Meeting of the U.S. Sections, The Combustion Institute, Pittsburgh, p. 26.

Faeth, G.M., (1999) "The Structure, Optical and Radiative Properties of Soot in Flame Environments: A Review," Proceedings of the 5th ASME/JSME Joint Thermal Engineering Conference, paper No. AJTE99-6530, San Diego, CA.

Faeth, G.M., Xu, F. and Krishnan, S.S. (1999) "Soot Formation in Premixed Flames," Fifth International Microgravity Combustion Workshop, NASA/CP-1999-208917, pp. 61-64.

Faeth, G.M. and Dai, Z. (1999) "Flow/Soot-Formation Interactions in Nonbuoyant Laminar Diffusion Flames," Fifth International Microgravity Combustion Workshop, NASA/CP-1999-208917, pp. 483-486.

Faeth, G.M., Dai, Z. and Lin, K.-C. (1999) "Laminar Soot Processes," Fifth International Microgravity Conference Workshop, NASA/CP-1999-208917, pp. 133-136.

Krishnan, S.S., Lin, K.-C., Wu, J.-S. and Faeth, G.M. (1997) "Optical Properties in the Visible of Soot Emitted from Turbulent Pool Fires." Proceedings of the ASME Winter Annual Meeting, Dallas, ASME, New York, HTD Vol. 352 (Vol. 2), pp. 39-48.

Krishnan, S.S., Lin, K.-C., Wu, J.-S. and Faeth, G.M. (1998) "Optical Properties of Soot in the Overfire Region of Large Buoyant Turbulent Diffusion Flames," Annual Conference on Fire Research, National Institute of Standards and Technology, Gaithersburg, MD, NISTIR 6242, pp. 29-30.

Krishnan, S.S., Lin, K.-C. and Faeth, G.M. (1999) "Scattering and Extinction Properties of Overfire Soot in Large Buoyant Turbulent Diffusion Flames," Proceedings of the National Heat Transfer Conference, Albuquerque, NM.

Krishnan, S.S., Lin, K.-C. and Faeth, G.M. (1999) "Refractive Index Properties of Soot Emitted from Buoyant Turbulent Diffusion Flames," Proceedings of the Joint Meeting of the United States Sections, The Combustion Institute, Pittsburgh, PA, pp. 560-563.

Krishnan, S.S., Lin, K.-C. and Faeth, G.M. (1999) "Extinction and Scattering Properties of Soot Emitted from Large Buoyant Turbulent Diffusion Flames," 34th National Heat Transfer Conference, ASME Paper No. NHTC 2000-12177, Pittsburgh, PA.

Lin, K.-C., Hassan, M.I. and Faeth, G.M. (1997) "Soot Formation in Freely-Propagating Laminar Premixed Flames," Fourth International Microgravity Combustion Workshop; NASA Conference Publication 10194, pp. 223-228.

Lin, K.-C. and Faeth, G.M. (1998) "Shapes of Nonbuoyant Round Luminous Hydrocarbon/Air Laminar Jet Diffusion Flames," Proceedings of the Spring Technical Meeting, Central States Section of the Combustion Institute, Pittsburgh, PA, pp. 357-362.

Lin, K.-C., Hassan, M.I. and Faeth, G.M. (1998) "Sooting Limits of Outwardly-Propagating Spherical Laminar Premixed Flames," Proceedings of the Spring Technical Meeting, Canadian Section of the Combustion Institute, Toronto, pp. 4-17 to 4-21.

Urban, D.L., Yuan, Z.-G., Sunderland, P.B., Linteris, G.T., Voss, J.E., Lin, K.-C., Dai, Z., Sun, K. and Faeth, G.M. (1998) "Structure and Soot Properties of Nonbuoyant Ethylene/Air Laminar Jet Diffusion Flames," 36th Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 98-0568.

Urban, D.L. and Faeth, G.M. (2001) "Soot Research in Combustion Science: Introduction and Review of Current Work," 39th Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 2001-0322.

Wu, J.-S., Krishnan, S.S., Lin, K.-C. and Faeth, G.M. (1997) "Measurements of the Optical Properties of Soot Emitted from Buoyant Turbulent Diffusion Flames at Long Residence Times," Proceedings of the Spring Technical Meeting, The Canadian Section of the Combustion Institute, Halifax, pp. 1-6 to 1-10.

Xu, F., Lin, K.-C., Faeth, G.M., and Sunderland, P.B. (1997) "Laminar Soot Processes," Fourth International Microgravity Combustion Workshop, NASA Conference Publication 10194, pp. 199-204.

Xu, F., Lin, K.-C., and Faeth, G.M. (1997) "Soot Formation in Laminar Premixed Methane/Oxygen Flames at Atmospheric Pressure," Proceedings of the Spring Technical Meeting, Central States Section of the Combustion Institute, Pittsburgh, pp. 332-336.

Xu, F., Lin, K.-C., and Faeth, G.M. (1998) "Soot Growth in Laminar Premixed Flames at Atmospheric Pressure," Proceedings of the Spring Technical Meeting, Canadian Section of the Combustion Institute, Toronto, pp. 4-7 to 4-11.

Xu, F., and Faeth, G.M. (1999) "Structure of the Soot Growth Region of Laminar Premixed Methane/Oxygen Flames," Proceedings of the Joint Meeting of the United State Sections, The Combustion Institute, Pittsburgh, PA, pp. 697-700.

Xu, F., and Faeth, G.M. (2000) "Soot Reaction and Flame Structure Properties of Laminar Acetylene/Air Diffusion Flames at Atmospheric Pressure," Proceedings of the Spring Technical Meeting, Central States Section, The Combustion Institute, Pittsburgh, PA, pp. 11-16.

Xu, F., and Faeth, G.M. (2000) "Soot Growth and Oxidation in Laminar Diffusion Flames," Proceedings of the Spring Technical Meeting 2000, Canadian Section of the Combustion Institute, Ottawa, pp. 19-1 to 19-6.

Xu, F., Dai, Z., and Faeth, G.M. (2001) "Suppression of Soot Formation and Shapes of Laminar Jet Diffusion Flames," Sixth International Microgravity Combustion Workshop, NASA/CP-2001-210826, pp. 173-176.

Xu, F., and Faeth, G.M. (2001) "Soot- and Smoke-Point Properties of Plane Laminar Jet Diffusion Flames," Proceedings of the Spring Technical Meeting, The Canadian Section, The Combustion Institute, Pittsburgh, PA.

Theses:

El-Leathy, A.M.(2001) "Effects of Fuel Type on Soot Formation and Oxidation in Laminar Diffusion Flames," Ph.D. Thesis, Mechanical Power Department, Helwan University, Cairo, Egypt, in progress.

Krishnan, S.S. (2000) "Optical Properties of Soot Emitted from Buoyant Turbulent Diffusion Flames," Ph.D. Thesis, Aerospace Engineering Department, The University of Michigan, Ann Arbor, MI.

Xu, F. (1999) "Soot Growth in Laminar Premixed Flames," Ph.D. Thesis, Aerospace Engineering Department, The University of Michigan, Ann Arbor, MI.

Reports:

Dai, Z., Lin, K.-C., Sunderland, P.B., Xu, F. and Faeth, G.M. (1997) "Laminar Soot Processes (LSP)," Report No. GDL/GMF 97-01, Department of Aerospace Engineering, The University of Michigan, Ann Arbor, MI.

Dai, Z., El-Leathy, A.M. Lin, K.-C., Sunderland, P.B., Xu, F. and Faeth, G.M. (2000) "Laminar Soot Processes (LSP)," Report No. GDL/GMF-00-03, Department of Aerospace Engineering, The University of Michigan, Ann Arbor, MI.

Oral Presentations (Invited):

Faeth, G.M. (1997) "Soot Growth in Laminar Premixed and Diffusion Flames," UIC, Spring Seminar Series, University of Illinois-Chicago, Chicago, IL.

Faeth, G.M. (1997) "Academic Perspectives on Combustion Research in the 21st Century," ASME Winter Annual Meeting, Houston, TX.

Faeth, G.M. (1997) "Structure and Soot Formation Processes of Premixed Flames," Graduate Research Seminar, School of Mechanical Engineering, Purdue University, W. Lafayette, IN.

Faeth, G.M. (1998) "Soot Formation in Laminar Premixed Flames," Mechanical Engineering Seminar, The Pennsylvania State University, University Park, PA.

Faeth, G.M. (1998) "Space Shuttle Observations of Soot-Containing Round Laminar Jet Diffusion Flames," Mechanical Engineering Seminar, University of Connecticut, Storrs, CT.

Faeth, G.M. (1999) "Observations of Nonbuoyant Laminar Diffusion Flames Using Space Shuttle Facilities," Department of Mechanical Engineering, University of California-Berkeley, Berkeley, CA.

Faeth, G.M. (1999) "Structure and Soot Properties of Laminar Jet Diffusion Flames," Gordon Conference on Gravitational Phenomena in Physico-Chemical Systems," New England College, Henniker, NH.

Faeth, G.M. (1999) "Flame/Flow Interactions During the Combustion of Gases," 52nd Annual Meeting of Division of Fluid Dynamics, American Physical Society, New Orleans, LA.

Faeth, G.M. (1999) "Structure, Optical and Radiative Properties of Soot in Flame Environments: A Review," 5th ASME/JSME Joint Thermal Engineering Conference, San Diego, CA.

Faeth, G.M. (2001) "Overview of NASA Research in Combustion Science," Space Studies Board, National Research Council, Washington, D.C.

Faeth, G.M. (2001) "Soot Formation and Oxidation in Flames: Findings from Ground-Based and Space-Shuttle Experiments," CNES Colloquium on Materials Research in Microgravity, Paris, France.

Faeth, G.M. (2001) "Micro-G and You: Space Research and Benefits on Earth in Physical Sciences/Combustion," Pan Pacific Conference on Micro-G, Los Angeles, CA.

Faeth, G.M. (2001) "Soot Formation and Oxidation in Flames," LCSR Seminar, University of Orleans, France.

Oral Presentations (Excluding Conference Papers that were presented orally):

Xu, F. Lin, K.-C. and Faeth, G.M. (1998) "Soot Formation in Laminar Premixed Methane/Air Flames at Atmospheric Pressure," 27th Symposium (International) on Combustion, Boulder, Co, poster paper.

Lin, K.-C., Faeth, G.M., Sunderland, P.B., Urban, D.L. and Yuan, Z.-G. (2000) "Shapes of Nonbuoyant Round Luminous Hydrocarbon/Air Laminar Jet Diffusion Flames," 28th Symposium (International) on Combustion, Edinburgh, Scotland, poster paper.

Dai, Z. and Faeth, G.M. (2000) "Hydrodynamic Suppression of Soot Formation in Laminar Coflowing Jet Diffusion Flames," 28th Symposium (International) on Combustion, Edinburgh, Scotland, poster paper.

Honors/Awards:

Faeth, G.M. et al., Best Propellants and Combustion Paper presented at the AIAA 37th Aerospace Sciences Meeting, Reno, NV, 1999.

Faeth, G.M., Invited Plenary Lecture, 5th ASME.JSME Joint Thermal Engineering Conference, San Diego, CA 1999.

Faeth, G.M., Invited Plenary Lecture, 30th AIAA Fluid Dynamics Conference, Norfolk, VA, 1999.

Faeth, G.M., Invited Plenary Lecture, 52nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, New Orleans, LA, 1999.

Faeth, G.M., NASA Public Service Medal, 1999.

Faeth, G.M., Horace H. Rackham Distinguished Dissertation Award, 1999.

Faeth, G.M., Highly-Cited Researchers Certificate, Institute for Scientific Information, Philadelphia, PA, 2000.

Faeth, G.M., Invited Plenary Lecture, 6th International Conference on Technologies and Combustion for a clean Environment, Porto, Portugal, 2001.

Participants:

Aung, K.T., Graduate Student Research Assistant, The University of Michigan, Ann Arbor, MI.

Hassan, M.I., Postdoctoral Research Fellow, The University of Michigan, Ann Arbor, MI.

Krishnan, S.S., Graduate Student Research Assistant (GSRA), The University of Michigan, Ann Arbor, MI.

Lin, K.-C., Postdoctoral Research Fellow, The University of Michigan, Ann Arbor, MI.

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